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BMDO/IST ONR N00014-91-J-4063 FINAL REPORT Dec. 31, 1993

**BALLISTIC MISSILE DEFENSE ORGANIZATION  
INNOVATIVE SCIENCE and TECHNOLOGY DIRECTORATE**

Current Grant Number: N00014-91-J-4063

Project Title: Communications Networks in Stressed Environments

Final Report - Period Covered: 1 Jan. 1991 - 31 Dec. 1993

S&T Agent: DR. RABINDER MADAN Agency: ONR

Principal Investigator: STEPHEN S. RAPPAPORT

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Secondary Investigator: T.G. Robertazzi

Project Classification: Unclassified

**Project Summary:**

Communications techniques and performance models are devised for communications networks in which mobile platforms, volatile traffic patterns, and interference are significant features. The main focus is on network organization and control configurations that support communications among semi-autonomous mobile platforms. Example platforms can support data gathering sensors and communications equipment aboard guided or maneuverable space vehicles, satellites, aircraft, ships or ground vehicles or persons. Network configurations with limited and/or shared communications resources are considered. Analytical models are devised to characterize major performance issues. Matters of concern include maintaining network connectivity with mobile platforms that have active communications links, methods for allocating communications resources to gateways, dynamic assignment of resources and access rights. Topics investigated have included: acquisition of spread spectrum signals, low-delay channel access protocols, call hand-off schemes, telecommunications traffic performance of mobile networks, computation vs. communication considerations, high speed packet switching, and aspects of self-organizing communications networks. A new framework has been developed that is based on the notion of multi-dimensional birth-death processes and which permits formulation of analytically tractable models for mobile communication networks that incorporate a considerable amount of physical complexity. The result is that teletraffic performance characteristics for many systems and alternative schemes can be numerically computed (rather than simulated by brute force Monte-Carlo type techniques). The results of the research provide increased understanding of effective techniques for rapid, reliable and ubiquitous communications among mobile users. Extensive publications of the work have been presented in the technical literature. A patent application has been filed. Some of the techniques have been incorporated in existing or developing systems.

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The Research Foundation  
of State University of New York

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February 3, 1994

Dr. Rabinder N. Madan  
Scientific Officer Code: 1114SE  
Office of Naval Research  
800 North Quincy Street  
Arlington, VA 22217-5000

RE: N0001491J4063

Dear Dr. Madan:

Enclosed please find three copies of Dr. Stephen Rappaport's final report for the above-referenced document. The four remaining copies have been distributed in accord with the contract's instructions.

Sincerely,

Katherine L. MacCormack  
Associate for Sponsored Programs

KLM:rb  
enc.

cc: Administrative Contracting Officer (1)  
Director, Naval Research Laboratory (1)  
Defense Technical Information Center (2) ✓  
Dr. S. Rappaport  
file 431-4342A  
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## CUMULATIVE LIST OF PUBLICATIONS AND PATENTS

*The publications listed below acknowledge support by SDIO/IST or BMDO/IST funding under ONR Grant No. N00014-91-J-4063 or its predecessor, ONR Contract No. N00014-85-K-0610 during the period Jan. 1, 1991 to Dec. 31, 1993. (List prepared January 19, 1994).*

### JOURNAL PUBLICATIONS

#### **January 1, 1991 - September 30, 1991**

S.S. Rappaport, "The Multiple-Call Hand-off Problem in High-Capacity Cellular Communications Systems," IEEE Transactions on Vehicular Technology, IEEE Trans. on Vehicular Technology, August 1991, vol. 40, no. 3, pp. 546-557.

A.A. Lazar and T.G. Robertazzi, "Markovian Petri Net Protocols with Product Form Solution", Performance Evaluation, Vol. 12, 1991, pp. 67-77.

S. Bataineh and T.G. Robertazzi, "Bus Oriented Load Sharing for a Network of Sensor Driven Processors", special issue on Distributed Sensor Networks of the IEEE Transactions on Systems, Man and Cybernetics, Sept. 1991, Vol. 21, no.5, pp. 1202-1205.

#### **October 1, 1991 - September 30, 1992**

S-W. Wang and S.S. Rappaport, "Signal-to-Interference Calculations for Corner-Excited Cellular Communications Systems," IEEE Trans. on Communications, Dec. 1991, vol. 39, no. 12, pp. 1886-1896.

#### **October 1, 1992 - May 31, 1993**

I.H. Chung and S.S. Rappaport, "Diversity Reservation Aloha," International Jour. of Satellite Communications, vol. 10, Oct. 1992, pp.47-60.

J. Shor and T.G. Robertazzi, "Traffic-Sensitive Algorithms and Performance Measures for the Generation of Self-Organizing Radio Network Schedules", IEEE Transactions on Communications, Vol. 41, No. 1, Jan. 1993, pp. 16-21.

#### **June 1, 1993 - December 31, 1993**

S.S. Rappaport, "Blocking, Hand-Off and Traffic Performance for Cellular Communication Systems with Mixed Platforms," IEE (British) Proceedings, Part I, Communications, Speech and Vision, Oct. 1993, vol. 140, no. 5, pp.389-401. (Funded in part by NSF Grant No. NCR-9025131).

T.G. Robertazzi, "Processor Equivalence for a Linear Daisy Chain of Load Sharing Processors", IEEE Transactions on Aerospace & Electronic Systems, Oct. 1993, pp. 1216-1221.

## BOOKS OR CHAPTERS PUBLISHED

### October 1, 1991 - September 30, 1992

S.S. Rappaport, "Models for Call Hand-Off Schemes in Cellular Communication Networks," Chapter 11, pp. 163-185, in *Third Generation Wireless Information Networks*, Kluwer Academic Publishers: Boston, Jan. 1992. (Funded in part by NSF Grant No. NCR-9025131).

### October 1, 1992 - May 31, 1993

S.S. Rappaport, "Communications Traffic Performance for Cellular Systems with Mixed Platform Types," pp. 177-201, in *Wireless Networks: Future Directions*, Kluwer Academic Publishers: Boston, 1993.

T.G. Robertazzi, editor, Performance Evaluation of High Speed Switching Fabrics and Networks: ATM, Broadband ISDN and MAN Technology, April 1993, IEEE Press, Piscataway N.J., 450 pages.

## PATENTS

### October 1, 1991 - September 30, 1992

S.S. Rappaport and H. Jiang, "CBWL: A New Channel Assignment and Sharing Method for Cellular Communication Systems," (A patent disclosure made to SUNY Research Foundation, May 1992.)

### October 1, 1992 - May 31, 1993

S.S. Rappaport and H. Jiang, "CBWL: A New Channel Assignment and Sharing Method for Cellular Communication Systems," (Patent filed February 1, 1993.)

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## **CONFERENCE AND WORKSHOP PRESENTATIONS**

### **January 1, 1991 - September 30, 1991**

S.S. Rappaport, "Modeling the Hand-Off Problem in Personal Communications Networks," Proc. IEEE Vehicular Technology Conference, VTC '91, St. Louis, May 1991, pp. 517-523.

S. Bataineh and T.G. Robertazzi, "Distributed Computation for a Bus Network with Communication Delays", Proceedings of the 1991 Conference on Information Sciences and Systems, The Johns Hopkins University, Baltimore MD, March 1991, pp. 709-714.

T.G. Robertazzi, "Why Most Stochastic Petri Nets are Non-Product Form Networks", Proceedings of the 1991 Conference on Information Sciences and Systems, The Johns Hopkins University, Baltimore MD, March 1991 (short paper), pg. 717. Extended version available as SUNY at Stony Brook College of Engineering and Applied Science Technical Report #598, March 8, 1991.

T.G. Robertazzi and A.A. Lazar, "Deflection Strategies for the Manhattan Street Network", Proceedings of the IEEE International Conference on Communications, Denver, Colorado, June 1991, pp. 1652-1658.

### **October 1, 1991 - September 30, 1992**

N. Srivastava and S.S. Rappaport, "Models for Overlapping Coverage Areas in Cellular and Micro-Cellular Communication Systems," Proc. IEEE Globecom '91, Phoenix, Dec. 1991, pp. 890-894.

S.S. Rappaport, "Communications Traffic Performance for Cellular Systems with Mixed Platform Types," Workshop Record, Winlab Workshop on Third Generation Wireless Information Networks, Rutgers University Winlab, New Jersey, April 28-29, 1992, pp. 131-158. (Funded in part by NSF Grant No. NCR-9025131).

S.S. Rappaport and G. Monte, "Blocking, Hand-Off and Traffic Performance for Cellular Communication Systems with Mixed Platforms," VTC '92 Denver, May 10-13, 1992, pp. 1018-1021. (Funded in part by NSF Grant No. NCR-9025131).

S.S. Rappaport, "Acquisition Schemes for Spread Spectrum Signals," SDIO/IST ONR Program Review Workshop on Communications and Superconducting Devices, Arlington, VA., Jan. 1992.

S.S. Rappaport, "Mobile and Wireless Information Networks: Teletraffic Performance," SDIO/IST ONR Program Review Workshop on Multi-Sensor Tracking/Survivable Communications and Mathematical Methods and Algorithms, Arlington, VA., July 13-14, 1992.

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Abernathy and T.G. Robertazzi, "Loading and Spatial Location in Wire and Radio Communications Networks", IEEE Military Communications Conference 1991, McLean, VA, Nov. 1991.

S. Bataineh and T.G. Robertazzi, "Ultimate Performance Limits for Networks of Load Sharing Processors", Proceedings of the 1992 Conference on Information Sciences and Systems, Princeton University, Princeton N.J., March 1992, pp. 794-799.

H-Y. Huang and T.G. Robertazzi, "Recursive Solutions for Discrete Time Queues with Applications to High Speed Switching Fabrics", Proceedings of the 1992 Conference on Information Sciences and Systems, Princeton University, Princeton N.J., March 1992, pp. 256-261.

H-Y. Huang and T.G. Robertazzi, "Performance Evaluation of the Manhattan Street Network with Input Buffers", Proceedings of the IEEE International Conference on Communications '92, Chicago, Ill, June 1992, pp. 202-206.

#### **October 1, 1992 - May 31, 1993**

H. Jiang and S.S. Rappaport, "CBWL: A New Channel Assignment and Sharing Method for Cellular Communication Systems, Proc. IEEE Vehicular Technology Conference, VTC '93, Secaucus, New Jersey, May 18-20, 1993, pp. 189-193.

T.P. Chu and S.S. Rappaport, "Generalized Fixed Channel Assignment with Hand-Off Priority in Micro-Cellular Communication Systems," Proc. IEEE Vehicular Technology Conference, VTC '93, Secaucus, New Jersey, May 18-20, 1993, pp. 607-610.

C. Purzynski and S.S. Rappaport, "Traffic Performance Analysis for Cellular Communication Systems with Mixed Platform Types and Queued Hand-Offs," Proc. IEEE Vehicular Technology Conference, VTC '93, Secaucus, New Jersey, May 18-20, 1993, pp. 172-175.

N.P. Newman and S.S. Rappaport, "Analysis of Multimedia PCN Medium Access Control in a Mixed Traffic Environment," Proc. IEEE International Conference on Communications, ICC '93, Geneva, May 23-26, 1993, pp. 177-181.

J.-W. Jeng and T.G. Robertazzi, "Buffer Management in Discrete Time Multiclass Models with Applications to High Speed Switching", Proceedings of the 1993 Conference on Information Sciences and Systems, The Johns Hopkins University, Baltimore MD, March 1993.

J. Sohn and T.G. Robertazzi, "Optimal Load Sharing for a Divisible Job on a Bus Network", Proceedings of the 1993 Conference on Information Sciences and Systems, The Johns Hopkins University, Baltimore MD, March 1993.

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H. Jiang and S.S. Rappaport, "CBWL for Sectorized Cellular Communications," Proc. 5th Intl. Conf. on Wireless Communications, Wireless '93, Calgary Alberta, Canada, July 12-14, 1993, pp. 503-508.

H. Jiang and S.S. Rappaport, "CBWL with Fast Channel Returning: A Scheme for Channel Sharing in Cellular Communications," Proc. IEEE International Conference on Universal Personal Communications, Ottawa, October 1993, pp.471-475.

S.S. Rappaport, "Traffic Performance of Cellular Communication Systems with Heterogeneous Call and Platform Types," Proc. IEEE International Conference on Universal Personal Communications, Ottawa, October 12-15, 1993, pp. 690-695.

H. Jiang and S.S. Rappaport, "Prioritized Channel Borrowing without Locking: A Channel Sharing Strategy for Cellular Communications," Proc. IEEE Globecom '93, Houston, Nov. 1993, pp. 276-280.

L.R. Hu and S.S. Rappaport, "Micro-Cellular Communication Systems with Hierarchical Macrocell Overlays," Workshop Record, Winlab Workshop on Third Generation Wireless Information Networks, Rutgers University Winlab Workshop '93, New Jersey, Oct. 19-20, 1993., pp. 143-173.

E. Foo and T.G. Robertazzi, "Packet Train Traffic in the Manhattan Street Networks using Deflection Routing", Proceedings of the Second International Conference on Computer Communications and Networks, San Diego, CA, June 1993, pp. 274-278.

S. Bataineh, T. Hsiung, and T.G. Robertazzi, "Closed Form Solutions for Bus and Tree Networks of Processors Load Sharing a Divisible Job", Proceedings of the 1993 International Conference on Parallel Processing, Chicago, Illinois, Aug. 1993.

J.-W. Jeng and T.G. Robertazzi, "Multimedia Information Based Deflection Routing Strategies for the Manhattan Street Network", Proceedings of the IEEE Military Communication Conference (MILCOM'93) 1993, Boston, Oct. 1993, pp. 128-132.

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## **TECHNICAL REPORTS**

**October 1, 1991 - September 30, 1992**

S.S. Rappaport, "Blocking, Hand-Off, and Traffic Performance of Cellular Systems with Mixed Platform Types," SUNY at Stony Brook, College of Engineering and Applied Sciences, Technical Report #610, February 1992.

T. Hsiung, and T.G. Robertazzi, "Performance Evaluation of Distributed Communication Systems for Load Balancing", SUNY at Stony Brook College of Engineering and Applied Science Technical Report 612, Dec. 17, 1991.

T.G. Robertazzi, "Processor Equivalence for a Linear Daisy Chain of Load Sharing Processors", SUNY at Stony Brook College of Engineering and Applied Science Technical Report 616, Jan. 22, 1992.

S. Bataineh and T.G. Robertazzi, "Ultimate Performance Limits for Networks of Load Sharing Processors", SUNY at Stony Brook College of Engineering and Applied Science Technical Report 623, April 2, 1992.

S. Bataineh and T.G. Robertazzi, "Closed Form Solutions for Bus and Tree Networks of Processors Load Sharing a Divisible Job", SUNY at Stony Brook College of Engineering and Applied Science Technical Report 627, May 27, 1992.

T.G. Robertazzi, "Recursive Solution of Equilibrium State Probabilities for Three Tandem Queues with Limited Buffer Space", SUNY at Stony Brook College of Engineering and Applied Science Technical Report 624, April 6, 1992.

J-W. Jeng and T.G. Robertazzi, "Evaluation of Continuous-Time Priority Queueing Systems under Different Buffering Strategies with Applications to High Speed Switching", SUNY at Stony Brook College of Engineering and Applied Science Technical Report 628, June 19, 1992.

J-W. Jeng and T.G. Robertazzi, "Multiclass Information Based Deflection Strategies for the Manhattan Street Network", SUNY at Stony Brook College of Engineering and Applied Science Technical Report 629, June 19, 1992.

E. Foo and T.G. Robertazzi, "Performance Evaluation of a Starlite-like Architecture for ATM Switching" SUNY at Stony Brook College of Engineering and Applied Science Technical Report 631, June 19, 1992.

S. Bataineh and T. Robertazzi, "Scheduling Algorithms for Divisible Jobs in a Multiprogrammed Multiprocessor System", SUNY at Stony Brook College of Engineering and Applied Science Technical Report 641, Sept. 30, 1992.

## *Technical Reports*

**October 1, 1992 - May 31, 1993**

H. Jiang and S.S. Rappaport, "CBWL: A New Channel Assignment and Sharing Method for Cellular Communication Systems," CEAS Technical Report No. 651, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

T-P. Chu and S.S. Rappaport, "Generalized Fixed Channel Assignment with Hand-Off Priority in Micro-Cellular Communication Systems," CEAS Technical Report No. 652, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

C. Purzynski and S.S. Rappaport, "Traffic Performance Analysis for Cellular Communication Systems with Mixed Platform Types and Queued Hand-Offs," CEAS Technical Report No. 653, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

H. Jiang and S.S. Rappaport, "CBWL for Sectorized Cellular Communications," CEAS Technical Report No. 654, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

H. Jiang and S.S. Rappaport, "CBWL with Fast Channel Returning: A Scheme for Channel Sharing in Cellular Communications," CEAS Technical Report No. 655, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

S.S. Rappaport, "Traffic Performance of Cellular Communication Systems with Mixed Platform and Call Types," CEAS Technical Report No. 656, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

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L.R. Hu and S.S. Rappaport, "Performance Analysis of Micro-Cellular Communication Systems with Hierarchically Overlaid Macro-Cells," CEAS Technical Report No. 658, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

N.P. Newman and S.S. Rappaport, "Analysis of Multimedia PCN Medium Access Control in a Mixed Traffic Environment," CEAS Technical Report No. 659, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

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J.-W. Jeng and T.G. Robertazzi, "Buffer Management in Discrete Time Multiclass Models with Applications to High Speed Switching", SUNY at Stony Brook College of Engineering and Applied Science (CEAS) Technical Report 643, Oct. 22, 1992.

J. Sohn and T.G. Robertazzi, "Optimal Load Sharing for a Divisible Job on Bus Networks", SUNY at Stony Brook College of Engineering and Applied Science (CEAS) Technical Report 649, Dec. 16, 1992.

J. Sohn and T.G. Robertazzi, "A Multi-Job Load Sharing Strategy for Divisible Jobs on Bus Networks", SUNY at Stony Brook College of Engineering and Applied Science (CEAS) Technical Report 665, April 16, 1993.

## **MANUSCRIPTS PENDING JOURNAL PUBLICATION ( Dec. 31, 1993)**

H. Jiang and S.S. Rappaport, "CBWL: A New Channel Assignment and Sharing Method for Cellular Communication Systems," IEEE Trans. on Vehicular Technology, Feb. 1994. (to appear - accepted for publication).

C. Purzynski and S. S. Rappaport, "The Multiple Call Hand-Off Problem with Queued Hand-Offs and Mixed Platform Types," (submitted for publication).

T.P. Chu and S.S. Rappaport, "Generalized Fixed Channel Assignment in Micro-Cellular Communication Systems," (submitted for publication).

N. Newman and S.S. Rappaport, "Analysis of Multimedia PCN Medium Access Control in a Mixed Traffic Environment," (submitted for publication).

L.R. Hu and S. S. Rappaport, "Micro-Cellular Communication Systems with Hierarchical Macrocell Overlays," (submitted for publication).

H. Jiang and S.S. Rappaport, "Prioritized Channel Borrowing without Locking: A Channel Sharing Strategy for Cellular Communications," (submitted for publication).

H. Jiang and S.S. Rappaport, "Channel Borrowing without Locking for Sectorized Cellular Communications," (submitted for publication).

S. Bataineh, T. Hsiung and T.G. Robertazzi, "Closed Form Solutions for Bus and Tree Networks of Processors Load Sharing a Divisible Job", To appear, IEEE Transactions on Computers.

S. Bataineh and T.G. Robertazzi, "Scheduling Algorithms for Divisible Jobs in a Multiprogrammed Multiprocessor System", submitted to Journal of Parallel and Distributed Computing.

S. Bataineh and T.G. Robertazzi, "Ultimate Performance Limits for Processor Networks Load Sharing Divisible Jobs", submitted to IEEE Transactions on Computers.

S. Bataineh and T.G. Robertazzi, "Manufacturing Networks: A Discrete Time Petri Type Network for Modeling Synchronization and Serialization", submitted to Performance Evaluation.

J. Sohn and T.G. Robertazzi, "Optimal Load Sharing for a Divisible Job on Bus Networks", submitted to IEEE Transactions on Aerospace and Electronic Systems.

J. Sohn and T.G. Robertazzi, "A Multi-Job Load Sharing Strategy for Divisible Jobs on Bus Networks", submitted to IEEE Transactions on Computers.

H.-Y. Huang, T.G. Robertazzi and A.A. Lazar, "A Comparison of Information Based Deflection Strategies", submitted to Computer Networks and ISDN Systems.